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Influence of filamentation on laser-induced modifications deep inside gallium arsenide

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Abstract

The conditions for internal structuring of gallium arsenide are thoroughly investigated using pulses with durations ranging from <200 femtoseconds to ~ 5 nanoseconds. In comparison to silicon, stronger evidence of filamentary modifications is reported.

In-bulk material interactions using tightly focused intense laser pulses give unique possibilities to create precise and functional 3D microstructures under the surface. In the past decades, the method has been successfully applied in transparent materials, generating tangible impact in areas such as integrated photonics, data-storage, fiber sensors and ophthalmology, etc. Recent years have witnessed an increasing interest for translating similar applications from dielectrics to more challenging semiconductors because of their strong technical importance in microelectronics and photonics industries [1]. However, experiments show that the intrinsic properties infrared-transparent semiconductors lead to much stronger propagation nonlinearities. These strongly distort the focusing conditions and affect the subsequent modification results [2,3]. Among the important nonlinear propagation effects, we can comment on the nonlinear refractive index in semiconductors which are orders of magnitude higher than those in dielectrics. Then self-focusing is inevitably expected at the considered laser fluence for material writing regimes, even in those relying on nanosecond pulses. Simulation and experiments already reveal the nonnegligible influence of self-focusing effect when ultrafast pulses are focused inside Si [2, 3]. For instance, a beam power-dependent focal shift is systematically observed [4]. Despite this and other propagation aspects have been widely investigated Si, the situations in other semiconductors are far less explored.

In this work, we investigate internal structuring of another important semiconductor, gallium arsenide (GaAs), which has important applications in electronics industries such as integrated circuits, light-emitting diodes or solar cells. 3D laser writing inside GaAs would offer new possibilities for adding new functionalities and innovative system designs. However, GaAs exhibits important differences in material properties in comparison to Si (Fig. 1a) from which we expect even stronger propagation nonlinearities. GaAs has 5 times higher nonlinear refractive index than Si. In addition, GaAs exhibits a direct bandgap and a two-photon absorption coefficient of 50 cm/GW at 300K and 1.55 μm [5]. In comparison, Si has an indirect bandgap with a two-photon absorption coefficient of just 0.76 cm/CW for similar conditions [6]. This must translate in stronger ionization and plasma effects affecting the beam. Taken these considerations together, a situation more subject to filamentation is expected in GaAs in comparison to Si.

The delivered pulse duration and energy density are obviously critical parameters for these questions. Therefore, we investigate internal writing of GaAs by using different pulse durations (from fs to ns) and different focusing conditions (numerical aperture (NA) from 0.3 to 0.85). The femtosecond laser pulses are produced by an Ytterbium source (Pharos, Light Conversion) combined with an optical parametric amplification (Orpheus, Light-conversion) for conversion at wavelength of 1550 nm. This wavelength is in the full-transparency domain of GaAs and Si. A minimum pulse duration of ~190 fs is delivered by the system. Picosecond laser pulses are obtained by using a grating pair arrangement to stretch the pulse duration in the range from 4 ps to ~20 ps as measured by a scanning autocorrelator. The nanosecond laser pulses are obtained by a fiber laser source (MWTech, PFL1550) with <5 ns pulse duration at 1550-nm central wavelength. A telescope is installed in the beam path to minimize the divergence and adjust the beam size for direct comparison with the ultrafast laser beams. The energy of the beams is controlled by the combination of a half wave plate and a polarizing beam splitter.

For the irradiation experiments, we use several infrared objective lenses (Olympus) with NA of 0.3, 0.45, 0.65 and 0.85, respectively. The later three lenses have a correction collar to compensate for spherical aberration induced by the refractive index mismatch between Air and Si. As the refractive index of GaAs is nearly identical to Si (Fig. 1a), we consider investigations can be performed with non-aberrated beams for all cases. The samples are from GaAs wafers of <100> crystal orientation and thickness of 600 μm (Neyco). The laser pulses are focused at 300 μm under the surface. For systematic comparisons, the modifications are obtained by illumination with 1000 repeated pulses as obtained by 1 second exposure time with a repetition rate of 1kHz. For detecting and observing the bulk modifications inside GaAs, an in-situ infrared imaging system is employed for lateral imaging. It is based on a custom arrangement with a long working distance objective lens (Mitutoyo, M Plan Apo NIR), a tube lens and an InGaAs camera.

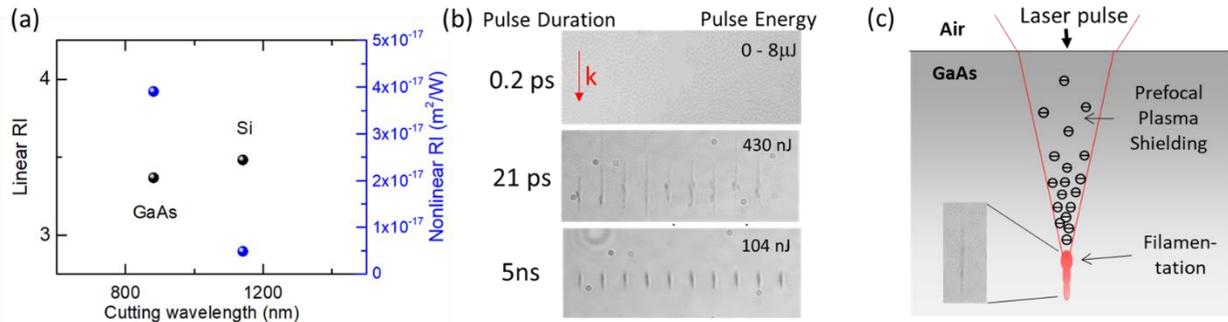


Fig. 1 (a) The comparison of material properties between GaAs and Si. RI represents refractive index. (b) The modification results of different pulse durations (NA=0.85). (c) Schematic of typical nonlinear effects that influence the laser focusing process inside GaAs. The inset shows the modification results corresponding to the filamentation regime.

The modification results in GaAs obtained with different pulse durations using a NA0.85 lens are illustrated with Fig. 1b. The results indicate a strong dependence of the pulse duration to achieve modifications. With the 200-fs pulse, no modification can be obtained even with pulse energies as high as 8 μJ. With 21-ps pulses, we can obtain modifications at 0.85NA focusing conditions but all attempts with lower NA failed. An important feature in this case is modifications which have much longer lengths compared to the modifications usually reported in Si [7]. As illustrated with Fig. 1c, this difference can be directly attributed to a situation more prone to filamentation phenomena because of reduced thresholds for plasma defocusing and the self-focusing. Another characteristic of 21-ps modification is the modest reproducibility of the modifications in comparison to what can be achieved in Si [7]. This could also be attributed to the stronger nonlinear distortions in GaAs, creating instabilities of energy delivery to the focal spots. With a stronger nonlinear response, we expect a situation exhibiting more sensitivity to experimental uncertainties that can be for instance local defects, surface contamination, laser fluctuations. When using 5-ns pulses, the long length and instability are mostly suppressed, as shown in the last row of Fig. 1b. In this case, lower NA focusing (0.65 and 0.45) can be used to achieve to modifications. However, less stability is found as we decrease the NA showing situations that are not fully free from important propagation nonlinearities.

The above results indicate that there is a strong requirement on both the pulse duration and the NA to achieve internal structuring of GaAs. Obviously, longer pulses and tighter focusing conditions are more favorable for preventing strong nonlinear propagation effects and then for obtaining stable modifications. However, an important conclusion from this work is on the range of laser parameters that fulfil the conditions for reliable 3D writing in GaAs. This must serve as a practical guideline for processing this material that hold promises for new applications in microelectronics. The comparison with Si in this work sheds also light on the underlying fundamental mechanisms involved in infrared laser interactions inside semiconductors.

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